Statistical Process Control (SPC) for Coordinate Measurement Machines. Using SPC and Monitoring of Standard Artifacts to Determine and Control Measurement Uncertainty in a Controlled Environment.

Rudolph N. Escher, Jr.
Oak Ridge Metrology Center,
Lockheed Martin Energy Systems, Inc.
U.S. Department of Energy Facilities
PO Box 2009
Oak Ridge, TN 37831-8091
Phone 423-576-3958
re8@y12.doe.gov

Abstract - The application of process capability analysis, using designed experiments, and gage capability studies as they apply to coordinate measurement machine (CMM) uncertainty analysis and control will be demonstrated. The use of control standards in designed experiments, and the use of range charts and moving range charts to separate measurement error into it's discrete components will be discussed. The method used to monitor and analyze the components of repeatability and reproducibility will be presented with specific emphasis on how to use control charts to determine and monitor CMM performance and capability, and stay within your uncertainty assumptions.

INTRODUCTION

We use a Moore M-48 Coordinate Measuring Machine (CMM) to calibrate step gages, ball bars and hole plates. The expanded uncertainty (k=2, approximately 95% confidence level) of the M-48 CMM was determined to be $\pm$ 0.3μm + 0.4 x 10^{-6} L micrometers (L is length in meters), using the decomposition method[1]. The problem statement is how do we monitor and control the calibration process to ensure that we maintain this level of reliability? Traditional methods of statistical process control, such as X-bar and R charts assume large lot production and are designed to detect changes in the process being monitored. Since calibrations are performed one at a time, with sometimes years between calibrations on the same artifact, standard control charting methods fall a bit short of what is needed to maintain process capability.

DISCUSSION

A link to the uncertainty analysis must be made to determine how and what to monitor for each calibration. Lets examine the process uncertainty for the M-48 CMM. Through repeated experiments and operating experience, we found that the following parameters play an important roll in process capability. Since the M-48 uses laser scales, the Edlϑn equation is used to convert pressure, temperature and humidity to wavelength correction. The largest source of uncertainty comes from temperature effects based on gradients, accuracy of the thermistors and the estimated thermal expansion coefficient of the artifact. The probe calibration, which is performed for each calibration, is another important variable. Since the M-48 CMM's movement is very slow, drift and radiant heat from lighting are also important parameters to consider.

UNCERTAINTY BUDGET

Machine error map reproducibility - The on-machine laser scales and external calibration laser were set to the same wavelength compensation number. This limits the error sources in the machine map to the reproducibility of the map, the index of refraction gradients between the two laser paths, the difference in laser frequencies and the interpolation errors between measured points of the map. The major uncertainty in the error map

was the $\pm$0.2μm (worst case) hysteresis. While 0.1μm of this is very repeatable and has been entered into a separate hysteresis map, the rest seems to be sporadic. We use the entire $\pm$0.2μm to be conservative. Taking this as a rectangular distribution we divide by 1.7 ($\sqrt{3}$) to obtain a 1σ uncertainty of $\pm$0.12μm.

The temperature gradient between the two beams is very small. The gradient everywhere near the table is < 0.05 °C yielding a related error of 0.05μm/m. Since the two beams are 200 mm apart in height the pressure gradient is negligible. The laser frequencies are within a few parts in 10^{-8} making them a negligible error compared to most of the other sources of errors. The error map smoothness and linear interpolation between the measured points, 25 mm apart, is indistinguishable from the map reproducibility stated above.

Wavelength (λ) compensation - λ is calculated from the atmospheric pressure, temperature and humidity using the "weather station" and loaded into the computer. The sources of error are: the Edlén Equation to convert pressure, temperature and humidity to λ correction, the uncertainty in pressure, temperature and humidity used in the equation and the systematic offset between the machine laser scale and the weather station.

The new Edlén equation based on the refractometry of air work at NPL is stated to be accurate to about 0.03x10^{-6}.

The 1σ thermometer calibration is conservatively .02 °C. The dependence of the Edlén equation on air temperature is approximately 10^{-6}/°C. The temperature calibrations produce negligible contributions, 0.02μm/m uncertainty in length.

The calibration of the barometer on the weather station has a reported uncertainty of 25 Pa. Given that 400 Pa represents a 10^{-6} effect on λ, the uncertainty associated with the barometer is 0.07x10^{-6}. The weather station sensors are in the M48 room near the machine and the systematic differences in pressure and temperature are negligible.

Probe ball diameter - The probe is calibrated against a 1 inch gage block for every measurement. The uncertainty of the gage block is 0.01 μm. The probe calibration varies

with each measurement and is therefor sampled in the check standard data.

Probe Scale Uncertainty - The probe is qualified by contacting the calibration gage block with the probe ball and comparing the probe output with the machine scales. If these differences are more than 0.050 μm the probe is inspected and recalibrated. For the uncertainty budget we assume the probe scale uncertainty is a rectangular distribution the same width as the qualification limit or 0.050/1.7= .030 μm.

Thermal expansion correction - The two sources of uncertainty associated with thermal expansion are the uncertainty in the thermometer measurement and the uncertainty in the value of the thermal expansion coefficient (TEC). Since there are thermometers placed on the artifact at 200 mm intervals, the uncertainties due to gradients in the artifact are negligible.

The thermometers are calibrated against an SPRT calibrated at NIST. The transfer uncertainty from NIST to the thermistors on the artifact are estimated to be 0.02 °C(1σ). For steel artifacts, with a TEC of 11.5 ppm, this yields an uncertainty of 0.23 μm/m(1σ).

The uncertainty in the TEC is dependent of the artifact. For steel end standards of unknown origins the default uncertainty is 10% (10^{-6}/°C). The length measurement uncertainty also depends on the difference between 20°C and the measurement temperature. The M48 room environmental control system maintains the artifact between 19.95°C and 20.05°C. This leads to an uncertainty of 0.05μm/m.

Contact deformation - The contact deformation can be ignored for unidirectional step gages because the deformation is the same on each step. For bi-directional step gages a small correction for deformation is made for gages which are not steel. The probe is calibrated with a steel gage block, resulting in the same deformation for the master block and the step gage. The Puttock and Thwaite (CSIRO Report, 1967) is used to make the correction for other materials. NIST has independently checked the deformation of a plane-sphere contact, through experimentation. No statistically significant differences have been found between theoretical and experimental results. The probe uses a very low force making uncertainties almost negligible. We estimate the corrections for this geometry have an uncertainty of < 0.40 μm.

Long term measurement reproducibility - The M48 performance is monitored by a number of check standards, including steel end standards (1 inch, 600mm, 800mm, 1000mm, and 20 inches) and Zerodur end standards (24 inches and 42 inches). A selected few are used with each calibration. Over an extended period of time over 30 calibrations have been done with each of the standards. The 1σ reproducibility for short artifacts (1 inch, 100mm) is 0.07 μm and ranges up to 0.10 μm for the 800mm and 1000mm standards. We also measured a 1 m Koba step gage a number of times using our normal procedure, which involves 6 separate runs. The standard deviations for each individual step was calculated and found to vary exactly as stated. This implies that the reproducibility is not strongly length dependent.

Reproducibility (1σ) = (0.07 + 0.03L)μm for L in meters

Part Temperature Gradients - The measured gradients on a meter step gage or end standard are less than 0.01°C. An average of the thermometer readings is used as the gage temperature. The uncertainty in length due to this averaging procedure is considered negligible compared to other sources of error.

Artifact geometry (alignment and gaging surfaces) - The parallelism and flatness of the gaging surfaces and the quality of the gage references can affect the quality of the calibration. These effects are considered for each customer gage and put in the error budget as needed.

APPLICATION & SPC

The selection of check standards and measurement protocol is made based on the uncertainty analysis and measurement dynamics. Since temperature, pressure and humidity play an important role in the M-48's uncertainty the room's environment is closely controlled and monitored. The check standards used to monitor and track process capability are chosen in part to detect changes in environmental parameters. This serves to provide a backup to our environmental monitoring system. By using a Zerodur Cylinder

which has a zero thermal expansion coefficient of zero and two steel check standards of varying length we can detect environmental changes which affect the calibration. The Zerodur Cylinder takes temperature out of the equation. One of the benefits we get from this is that it lets us detect errors due to drift in the thermistors used to monitor room, machine or artifact temperature. If all of the check standards are out of control, then we know that temperature was not the culprit but humidity, pressure, and probe calibration are key suspects.

X-bar, Range (R), and moving R charts are used to monitor process capability and measurement repeatability of the check standards. The moving range chart estimates process variability. A spike in the moving range chart could detect an environmental change that affects all the check standards equally. When we have historical data on the artifact under calibration we also compare the standard deviations and repeatability between calibrations.

Using these techniques we've been able to detect small changes in room environment, small movements of the probe calibration gage

block and small bends in artifacts which occurred between calibrations.

EXAMPLES

Temperature effects - In 1996 The Oak Ridge Metrology Center ran an experiment to determine the effects of having a person in the M-48 CMM room on artifact temperature. Figure 1 illustrates the location of the person for the experiment. Drawing 1 shows the artifact and thermistor setup on the machine.

Figure 1

Artifacts and Thermistor Locations

42" Zerodur

900 MM
#7   #8

800 MM
#6   #5

Mitutoyo 24"bar #002

8(2)   7(2)   6(2)   5(2)

12" Chk. Std.
2   3

1" Chk. Std.
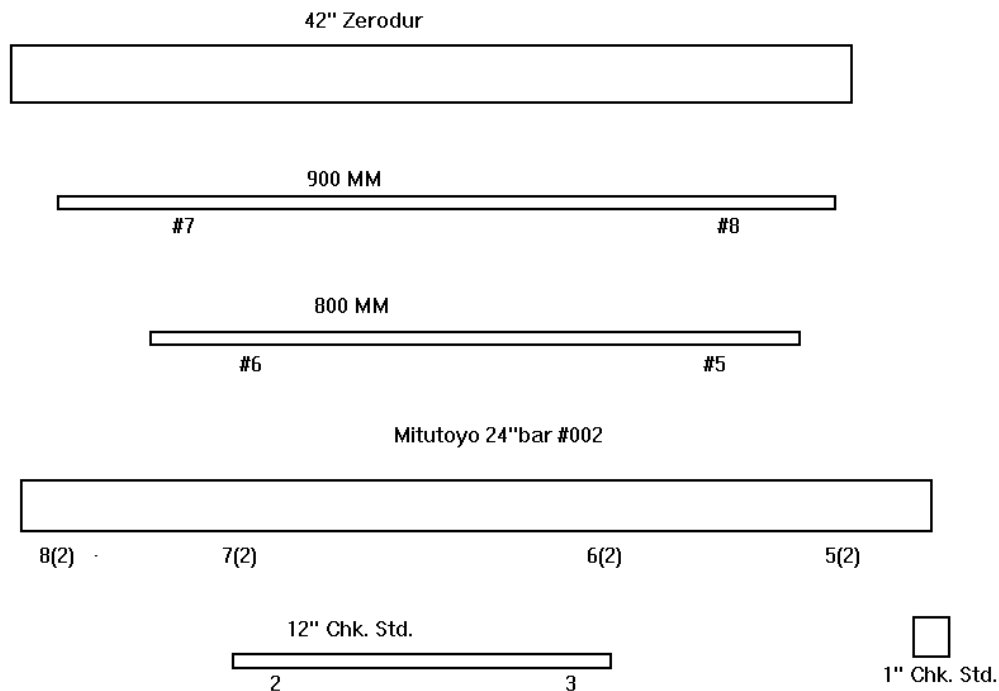
Drawing 1.

Note: (2) Indicates thermistors on Station #2 (M-259748)

Figure 2

For the experiment a person walked into the room and stood in the position indicated in Figure 1 for five minutes. The person then left the M48 room. Seen in Figure 2.

Figure 3 is a plot of the temperature of the 900mm gage block. It demonstrates the effect that the heat load of one person in the M-48

measurement room has after five minutes. It took 1 hr. and 45 minutes for the temperature of the 900-mm rectangular block to stabilize.
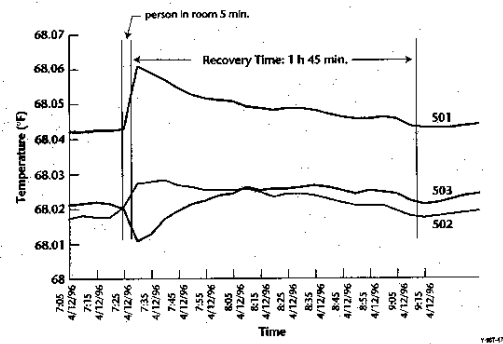
Figure 3

Chart 1.
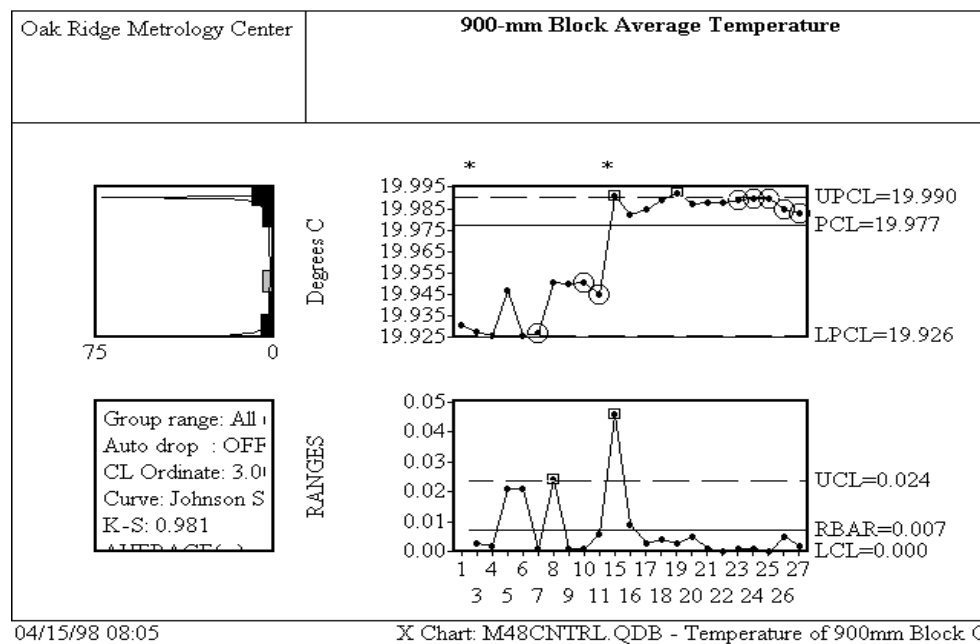
Calibration routine changed - On November 11, 1998 the Moore bar check standard was replaced with two gage blocks. This allowed us to modify our calibration routine to reduce the calibration time, thereby reducing drift error.

Gage blocks have a lower uncertainty than a Moore bar, which also gives us the ability to detect finer process changes. The new configuration is illustrated in Drawing 1.

After making this configuration change and changing the calibration routine, we saw a step

change in our temperature control. You can see this in the series of temperature control charts

Chart 2.

Oak Ridge Metrology Center	**900-mm Block Average Temperature** Before November 11, 1998

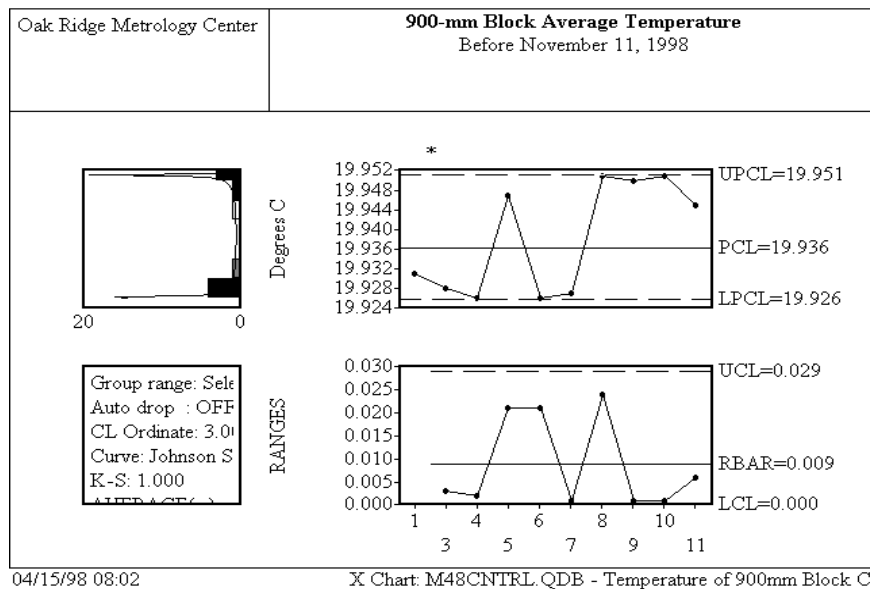19.952
19.948
19.944
19.940
Degrees C   19.936 ——————— PCL=19.936
19.932
19.928
19.924

UPCL=19.951
LPCL=19.926

Group range: Sele
Auto drop : OFF
CL Ordinate: 3.0
Curve: Johnson S
K-S: 1.000

0.030 — — — — — UCL=0.029
0.025
0.020
RANGES 0.015
0.010 ——————— RBAR=0.009
0.005
0.000 ——————— LCL=0.000

1   3   4   5   6   7   8   9   10   11

04/15/98 08:02   X Chart: M48CNTRL.QDB - Temperature of 900mm Block C

(Charts 1, 2 & 3) for the 900-mm rectangular block. The average temperature became more stable and moved closer to 20°C. This demonstrates how you can use statistical information to guide you in making minor process changes that can have a significant impact on repeatability.

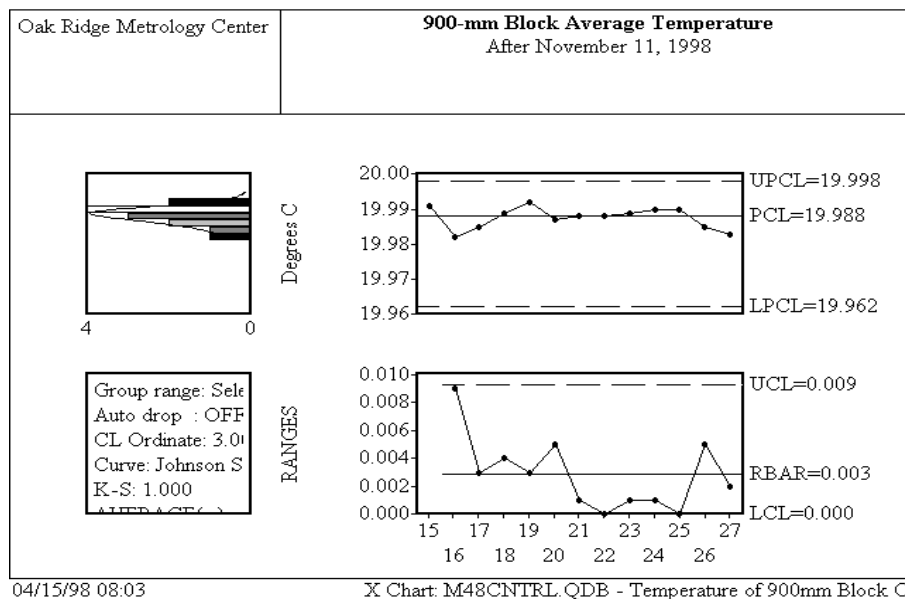Chart 1, illustrated on the following page, specifically shows the affect on the control chart and how the process moved in an incremental manner. Chart 2 shows the process control chart prior to changing the calibration routine. Chart 3 shows the new control parameters and improved process repeatability.

CONCLUSION

Through the use of control standards and statistical methods we can monitor and improve

the calibration process. Statistical methods can be used to validate designed experiments and subsequently monitor and maintain process capability and reliability.

Chart 3.

Oak Ridge Metrology Center	**900-mm Block Average Temperature** After November 11, 1998

20.00 — — — — — UPCL=19.998
19.99 ——————— PCL=19.988
Degrees C   19.98
19.97
19.96 ——————— LPCL=19.962

Group range: Sele
Auto drop : OFF
CL Ordinate: 3.0
Curve: Johnson S
K-S: 1.000

0.010 — — — — — UCL=0.009
0.008
0.006
RANGES 0.004
0.002 ——————— RBAR=0.003
0.000 ——————— LCL=0.000

15   16   17   18   19   20   21   22   23   24   25   26   27

04/15/98 08:03   X Chart: M48CNTRL.QDB - Temperature of 900mm Block C

REFERENCES

Walpole & Myers, *Probability and Statistics for Engineers and Scientists,* Fourth Edition, 1989, Macmillan, New York.

Montgomery, ***Introduction to Statistical Quality Control,*** Second Edition, 1991, John Wiley & Sons, New York.

Machines by Measurement Decomposition and Utilization of Reference Artifacts

---

[1] B. Rasnick, B. Cox, M. Sherrill, *Determination Measurement Uncertainty on Coordinate Measurement*